Design of a Walking Assistance Lower Limb Exoskeleton for Paraplegic Patients and Hardware Validation Using CoP

Regular Paper

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Abstract The design of an assistive lower limb exoskeleton robot for paraplegic patients that can measure the centre of pressure is presented. In contrast with most biped walking robots, the centre of pressure (CoP) or zero moment point (ZMP) has not been actively used in the operation of exoskeleton robots. In order to measure CoP in our exoskeleton robot, two kinds of force sensor units are installed in the exoskeleton: low profile force sensors in foot modules to measure the human weight transferred to the ground and a load cell at the shank frame to measure the supporting force. The CoP of the exoskeleton robot is calculated from the above force sensors, an inclinometer at the waist, and the positions of 14 DOF exoskeleton joints with an algorithm to change the fixed pivot using a foot contact sensor. Experiments on an able-bodied person wearing the designed exoskeleton and walking on the ground are performed to validate the designed hardware system. Through the experiments, the trajectory of the CoP of the exoskeleton with a wearer are calculated based on the proposed algorithm and it is compared with the value measured by a commercial pressure measurement system.

1. Introduction

1.1 Background

As a method of providing walking assistance for paraplegic patients, exoskeleton-type assistive devices have recently received a great deal of attention, since these devices can provide full mobility similar to human walking. Since the ability to walk is an essential function of human beings, many paraplegic patients - who are unable to walk - dream of walking again. Most of them have had critical accidents that caused their paralysis, and the possibilities of accidents are quite high in modern society. Exoskeleton-type walking assistive devices have been developed for this reason and can achieve patients' dream of walking, whereas wheelchairs only help them to move.

In general, an exoskeleton device refers to a device that is worn by a user to perform a particular function: augmenting human power, assisting walking, supporting heavy loads, and so on [1,2]. Notable studies on exoskeletons for paraplegic patients have recently been reported in the U.S. and Israel. The University of California, Berkeley, and Berkeley Bionics have recently developed eLEGS [3, 4], which is a lower-extremity exoskeleton. The eLEGS uses an arm angle and crutch load to determine the user's intention. The particular sequences of the sensor signals are used to determine the proper time to be operated according to the human intention to walk while in eLEGS. An Israeli company, Argo Medical Technology, has recently developed another exoskeleton device named ReWalk. However, no papers relating to ReWalk have been published, and their website only describes ReWalk briefly [5].

Even though researchers in many institutions have been struggling to find a suitable method to improve the performance of exoskeletons, there are surprisingly few studies reporting on exoskeleton performance [2]. Furthermore, exoskeletons are still in the early stages of their development [6].

1.2 Centre of Pressure in an Exoskeleton Robot

Since the wearer does not have the ability to move his or her legs actively, the exoskeleton has to actively move links that guide the human legs. In this regard, the exoskeleton for paraplegic patients is close to a humanoid robot in terms of active motion. As the concept of the ZMP is generally used for many biped humanoid robots, it can be used to check stability while an exoskeleton worn by a patient is operated. In addition, it could also be used to estimate the human intention of walking, since one of the fundamental walking principles is the translation of body mass - more exactly, the centre of mass [7] - which is deeply related to the ZMP.

Instead of using the ZMP, the CoP is used in the assistive exoskeleton for the purposes of detecting the human intention to walk and checking stability in this study. This approach can be deemed valid for the following two reasons: the coincidence between ZMP and CoP and the popularity of CoP in the medical field. Both ZMP and CoP are the coincident point on the supporting plane - normally flat ground - as long as there exists contact between a foot and the ground [8, 9]. In general, the translation of centre of gravity, which is deeply involved in ZMP and CoP, is considered one of the dominant mechanisms of human walking [7]. Based on the principle of human walking, the CoP may be used when we operate an exoskeleton or when we determine the intention of the wearer. While the ZMP is essentially used in the control of humanoid robots [10, 11], the concepts of CoP or ZMP have not been utilized well in the area of exoskeleton robots. In order to use CoP in an exoskeleton robot, a proper design and the validation of hardware should first be accomplished.

For this purpose, the design and validation of hardware using the CoP of a walking assistive lower limb exoskeleton for paraplegic patients have been performed in the first step of this study. The design concept of the exoskeleton is discussed in section 2 and a theoretical study of position analysis and CoP is performed in section 3. Details of structural design, with consideration of human biomechanics, sensor design and the data acquisition system of a lower limb exoskeleton are explained in section 4. Finally, walking experiments for the validation of hardware are discussed in section 5.

2. Design Concept

To assist paraplegic patients who cannot move their legs independently, the exoskeleton helps the motion generation of the lower limbs of the wearer. In order to minimize discomfort for the wearer, the lower limb exoskeleton is designed with 3 degrees of freedom (DOF) of the hip joint, 1DOF of the knee joint and 3DOF of the ankle joint, making 7 DOF in a leg. Among these 7 DOF joints in a leg, two joints - the hip and knee joints - are activated in the sagittal plane. Electric motors are used for the actuators due to their higher efficiency and lower weight. Hydraulic actuators are less competitive in this application since they require basic components, such as a pump, reservoir, manifolds, and so on. The electric motors are mounted with gear sets designed to provide proper performance for activating joints. To reduce the burden and for the actuators to move its links, lightness has been considered in the design process. In addition, another important consideration in the design of the exoskeleton is the method for firmly mounting the exoskeleton onto the human's lower extremities without discomfort. Since we have considered the CoP as a method for determining the intention of a patient to walk, the positions of all the contact points where the forces are transferred from the exoskeleton and the wearer to the ground must be known. For this purpose, we use the following sensors:

a) Angle sensors at all joints (14 DOF in the legs)
b) A force sensor measuring the reaction between the exoskeleton and the ground
c) A force sensor measuring the reaction between the wearer and the exoskeleton's foot
d) A ground contact sensor system in the exoskeleton foot
e) The measurement of the torso angle as a reference of orientation

The angle sensors on all the joints can provide the relative positions of the links - including both feet, which are

important parts in finding the CoP - through a kinematic position analysis of the exoskeleton. Force sensors are classified into 2 categories, as listed in (b) and (c) above. These force sensors give the reactions between the exoskeleton worn by a user and the ground, which are used to calculate the CoP with the joint angles. Since the angle sensors only provide relative positions, more information is needed to determine the absolute positions. By using the sensors listed in (d) and (e), we can determine these positions. The ground contact sensor system (d) indicates whether the foot touches the ground, as well as the location of the contact point of the bottom of the exoskeleton foot. When foot contact occurs, the absolute position can be determined by fixing the contacting foot by assuming that the foot is physically fixed on the ground. While the 4 categories of sensors are enough to measure the location of the CoP of the exoskeleton, one more sensor is required due to the error of each angle sensor. Even though the error of each joint sensor is not large, the accumulated error can be serious due to the characteristics of the serial mechanism. Therefore, the utilization of an inclinometer that measures absolute angles to the gravity vector is needed, and it can be used as a reference when it is attached to a particular element of the exoskeleton.

The exoskeleton is worn by a human and, thus, safety is a critical factor. To prevent injuries caused by the actuators through any malfunction of the system, safety elements such as mechanical stoppers should be implemented on the joints. These elements will secure the safety of the activated joints upon any unexpected malfunction of the system.

The user is not stable when only wearing the exoskeleton since the two active joints in the knee and hip lack of support. Incorporating additional active joints can enhance the stability but will also increase the weight as well as the power requirement of each joint. To supplement the stability problem, forearm crutches that can be controlled by the upper limbs of the user are used. Forearm crutches will increase the walking stability of the wearer of the exoskeleton by providing additional controllable tools to support the body on the ground. This paper deals with the design of a lower limb exoskeleton that can acquire the CoP of a human-machine system for the walking assistance control of paraplegic patients. The design of the crutch sensor system to measure the force and the location of tip is not presented here.

3. Theoretical Study of the Exoskeleton

3.1 Position Analysis of the Exoskeleton

Considering a lower limb exoskeleton with 14 DOF in total, the kinematic model for the exoskeleton is shown in figure 1 (a). As described in the previous section, an inclinometer is used to provide a reference for the posture of the exoskeleton. It is located on the midpoint of the waist of the exoskeleton to measure the torso angles of the human, since the motion of the torso is smooth, balanced and cyclic compared to that of other locations of the exoskeleton. To analyse the positions of the links based on the midpoint of the waist, 2 Denavit-Hartenberg (DH) models with 9 DOF on each limb are considered, as shown in figure 1 (b). 2 DOF among the 9 DOF represent the rotation angles of the torso in the sagittal plane and the coronal plane, while the other 7 DOF are based on the leg of the exoskeleton. Table 1 shows the corresponding DH parameters.
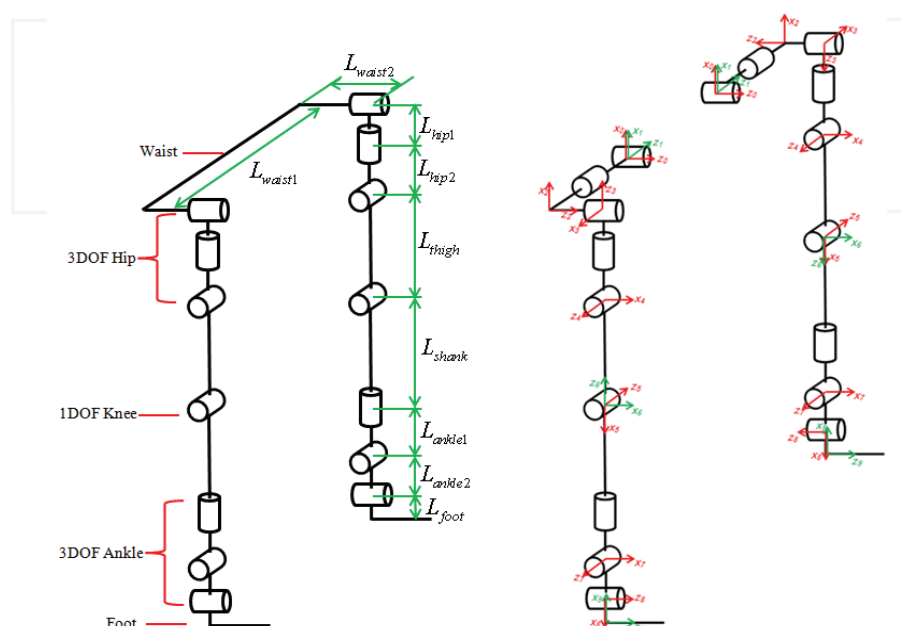

Figure 1. (a) 14 DOF Kinematic model of the exoskeleton (b) 9 DOF of Denavit-Hartenberg model of 2 legs of the exoskeleton and axes on the joints

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	Right Leg			
Joint i	d_i (mm)	θ_i (°)	a_i (mm)	α_i (°)
1	0	0	0	90
2	$-L_{waist1} / 2$	0	0	-90
3	L_{waist2}	90	0	90
4	$-\left(L_{hip1} + L_{hip2}\right)$	90	0	90
5	0	-90	L_{thigh}	180
6	0	-90	0	90
7	$-\left(L_{shank} + L_{ankle1}\right)$	0	0	90
8	0	-90	L_{ankle2}	-90
9	0	180	$-L_{foot}$	180

Table 1. DH parameters of the lower limb exoskeleton

With the DH parameters in Table 1, the transformation matrix from the $i-1^{th}$ to i^{th} coordinate, $^{i-1}A_i$, may be obtained as:

$$^{i-1}A_i = T(z,d_i)T(z,d_i)T(x,a_i)T(x,\alpha_i) \qquad (1)$$

where:

$$T\left(z,d_i\right) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}, T\left(z,\theta_i\right) = \begin{bmatrix} \cos\theta_i & -\sin\theta_i & 0 & 0 \\ \sin\theta_i & \cos\theta_i & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T\left(x,a_i\right) = \begin{bmatrix} 1 & 0 & 0 & a_i \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, T\left(x,\alpha_i\right) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\alpha_i & -\sin\alpha_i & 0 \\ 0 & \sin\alpha_i & \cos\alpha_i & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (2)$$

The result of the calculation is:

$$^{i-1}A_i = \begin{bmatrix} \cos\theta_i & -\cos\alpha_i\sin\theta_i & \sin\alpha_i\sin\theta_i & a_i\cos\theta_i \\ \sin\theta_i & \cos\alpha_i\cos\theta_i & -\sin\alpha_i\cos\theta_i & a_i\sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (3)$$

The transformation matrix from each ith link to the base link, 0, can then be represented as:

$$^0A_i = ^0A_1 ^1A_2 \cdots ^{i-1}A_i \qquad (4)$$

The kinematic model has a base link on the midpoint of the waist, while the other links of the legs are in relative positions to the base link. In order to represent the joint positions of the exoskeleton robot in global coordinates, a fixed pivot foot on the ground has to be determined first of all. The other positions can then be represented relative to the fixed pivot. It is important to change the pivot at the moment in time when the pivot foot is firmly stepping onto the ground so as to keep moving continuously. Figure 2 shows the algorithm for changing the pivot for a proper walking model. Once the pivot foot is changed, the position of the pivot is set to a new reference position that is fixed on the ground.

When a step change occurs, the pivot moves to the end position in the opposite foot. A simple schematic of a step change is shown in figure 3. Here, the backbone is the base link and is labelled link 0. $^n\mathbf{p}_m{}^i$ represents the local position of origin attached to link m from the view of the origin of the coordinate on link n in the ith step.
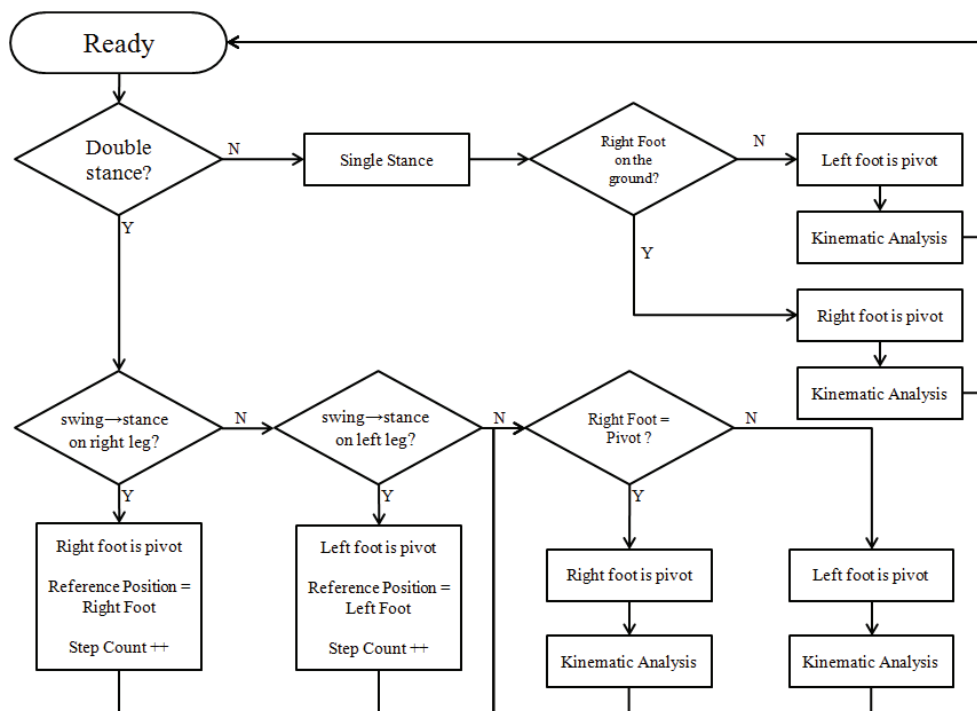

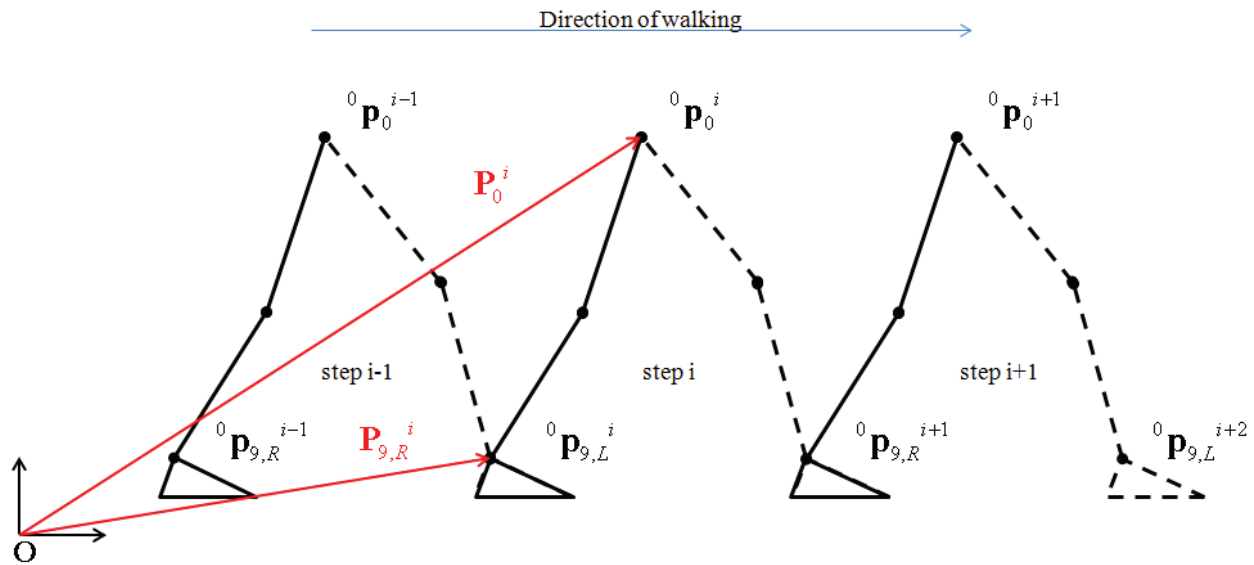**Figure 2.** Algorithm for changing pivot foot in kinematic analysis

Figure 3. Schematic of a step change

For example, $^{0}\mathbf{p}_{0}^{\,i-1}$ denotes the position of origin of link 0 from the view of the origin of link 0 for the $i-1^{\text{th}}$ step, and is (0,0,0). $^{0}\mathbf{p}_{9,R}^{\,i}$ is the position of origin of link 9 on the right leg from the view of the origin of link 0 for the ith step. While the small letter $\mathbf{p}$ represents the position in a local coordinate, the capital represents the position in the global coordinate. O is the origin of the global coordinate and $\mathbf{P}_{9,R}^{\,i}$ represents the position of link 9 on the right leg for the ith step. If the reference position is determined in the ith step as:

$$\mathbf{P}_{\text{ref}}^{\,i}\begin{cases}=\mathbf{P}_{9,R}^{\,i-1}\ \left(\text{when right foot becomes the pivot}\right)\\ =\mathbf{P}_{9,L}^{\,i-1}\ \ \left(\text{when left foot becomes the pivot}\right)\end{cases} \quad (5)$$

the global positions of links of the exoskeleton then become:

$$\mathbf{P}_{\text{m}}^{\,i}\begin{cases}=^{0}\mathbf{p}_{\text{m}}^{\,i}-^{0}\mathbf{p}_{9,R}^{\,i}+\mathbf{P}_{\text{ref}}^{\,i}\ \left(\text{when right foot is the pivot}\right)\\ =^{0}\mathbf{p}_{\text{m}}^{\,i}-^{0}\mathbf{p}_{9,L}^{\,i}+\mathbf{P}_{\text{ref}}^{\,i}\ \left(\text{when left foot is the pivot}\right)\end{cases} \quad (6)$$

3.2 Centre of Pressure

The CoP is defined in biomechanics as the point where the resultant force of all ground reaction forces acts. This terminology is frequently used in the field of biomechanics. On the other hand, ZMP is a criterion for dynamic stability that is generally used in the field of biped walking robots. It was theoretically proven that the CoP is the coincidence point with ZMP [8] when the two feet are in contact with a plane or when one foot is in surface contact, except for the case of contact with the foot's edge. The CoP has an important meaning in the walking process, as described at the beginning of this paper.

Since there are limited contact points on the exoskeleton, the CoP can be calculated by the following definition:

$$\mathbf{P}_{\text{CoP}}=\frac{\sum\left(\mathbf{n}\times\left(\mathbf{P}_{\text{i}}\times\left(\mathbf{F}_{\text{i}}\cdot\mathbf{n}\right)\right)\right)}{\sum\left(\mathbf{F}_{\text{i}}\cdot\mathbf{n}\right)} \quad (7)$$

where $\mathbf{P}_{\text{CoP}}$ represents the location of the CoP in the global coordinate, $\mathbf{n}$ is the normal vector of the ground, and $\mathbf{F}_{\text{i}}$ is the force of the contact point i. With an assumption that x is the coordinate in the forward direction and y is that in the side direction on the ground, the equation can be expressed in the form of:

$$\left(x_{\text{CoP}},y_{\text{CoP}}\right)=\left(\frac{\sum F_{\text{n,i}}x_{\text{i}}}{\sum F_{\text{n,i}}},\frac{\sum F_{\text{n,i}}y_{\text{i}}}{\sum F_{\text{n,i}}}\right) \quad (8)$$

where $\left(x_{\text{CoP}},y_{\text{CoP}}\right)$ represents the coordinate of the CoP, $\left(x_{\text{i}},y_{\text{i}}\right)$ is the coordinate of contact point i, and $F_{\text{n,i}}$ is the force component normal to the ground at the contact point i. In this initial stage of development, we only considered the contact points of four force sensors in both feet and two force sensors in both shanks. In the case of walking with crutches, the locations of the end tips of the crutches and the measurement of the force at these points should be taken into consideration in equation (8). The sensors measuring the ground contact forces are explained in the next section.

4. Hardware Design of the Lower Limb Exoskeleton

According to the concept of design in section 2, a lower limb exoskeleton has been designed, as shown in figure 4. The details of the designed exoskeleton are described in the following sections. Considerations as to the structural design, low profile force sensors in the exoskeleton foot to measure the human weight, the load cell at the shank frame to measure the supporting force, the ground contact sensor, the inclinometer at the waist, the actuators

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and the data acquisition system are discussed in this section.

Figure 4. Designed lower limb exoskeleton

4.1 Structural Design

A circular pipe shape has been selected for the links due its advantage of lightness, since the shape has a high area inertia of moment compared with the other cross-sectional shapes in all directions, meaning better strength in shear and bending moment for the unit mass. Duralumin is selected as the material of the link, on the basis of low cost.

The proper dimensions have been selected through a strength simulation. Figure 5 shows the conditions and assumptions in the simulation. Since the weight of a human leg is about 10% of a person's total weight, 80N force is reasonable if the person is assumed to weigh 800N for tolerance. The worst load condition is assumed such that the link bears shear due to 80N force vertically, as shown in figure 5 (a). Furthermore, it is assumed that the load is concentrated on the knee joint. This may be considered valid because the distribution of weight due to the gravity of a leg is more concentrated on the areas near the hip than those near the ankle, and thus the assumed concentrated load condition is worse than the original condition. The results of the simulation give a stress of 88.55MPa at the maximum level and a safety factor of about 5.7, compared to the yield strength of the link (505MPa, duralumin), which is considered safe in an impulse condition, at the weakest point of the link. Solidworks 2010 was used as the simulation tool and the graphical results of the simulation are shown in figure 5 (b).
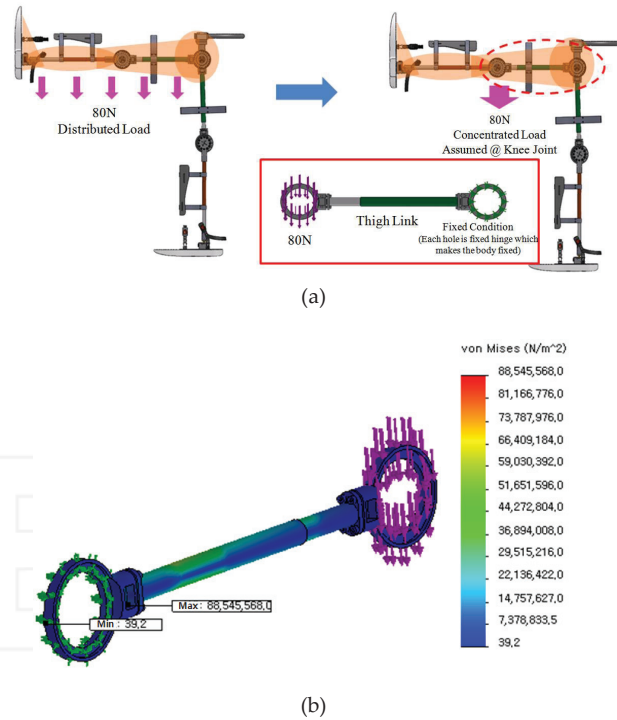

Figure 5. (a) Assumed condition for the stress simulation of the thigh link (b) Results of the stress simulation

The connection method between the exoskeleton and human should also be considered in the design. The harness in this system should provide a firm mount to assist human motion, while comfort and ergonomics are considered. For this purpose, a backpack frame with a cushioned shoulder, waist bands and non-stretchable bands with air cushions were used at the mounts of the torso, thighs and shanks, respectively. The exoskeleton has other connection points at its feet, which are important mounting locations, with latchet-type bindings. The bindings have reliable strength since they were originally designed for the purpose of climbing. The mounts' parts are shown in figure 6.

The designed structure of the exoskeleton has the dimensions indicated in Table 2 in the kinematic model of figure 1, and its weight is 130N.
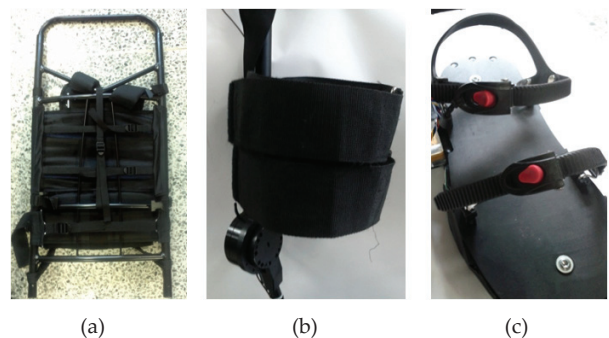

Figure 6. The mounting elements of the exoskeleton: (a) Backpack frame with cushioned bands for torso mount (b) Bands with air cushions for thigh mount (c) Ratchet bindings at the foot mount

	Dimensions (mm)
L_{waist1}	450
L_{waist2}	270
L_{hip1}	0
L_{hip2}	101
L_{thigh}	420
L_{shank}	480
L_{ankle1}	0
L_{ankle2}	0
L_{foot}	55

Table 2. Dimensions of the designed exoskeleton

4.2 Sensors

There are angle sensors, potentiometers and encoders for all 14 joints of the exoskeleton, as can be seen in the model of figure 1 (a). Potentiometers are used for the angle sensors at the un-actuated 10 joints (4 at the hips and 6 at the ankles). The 3 DOF hip joint is composed of a passive yaw joint, a passive roll joint and an active pitch joint, as shown in figure 7 (a). To reduce the rotational friction at the roll and yaw joints, a block type bushing housing unit and brass materials are used. Here, no axial force is applied to the potentiometers by mechanical stoppers and pure rotational motion is transferred to the potentiometers. Figure 7 (b) shows the design of the 3 DOF ankle joint. In the square frame at the ankle, potentiometers for measuring the pitch and roll joint angle are set orthogonally and they are connected to the shafts of the gimbal mechanism. At the centre of the gimbal mechanism, a ball joint is located and its end is connected to the gimbal mechanism. Above the ball joint, a potentiometer for the yaw angle is embedded and it is connected to the shank frame, permitting only rotational motion.

The absolute angles of the potentiometers are calibrated when they are assembled, while those of encoders are recalibrated using the mechanical stopper after every start-up [12,13].

An inclinometer was used to measure the torso angles and is attached to the midpoint of the waist, as shown in figure 8. Ground contact sensors and force sensors are also installed in the exoskeleton robot. For the detection of the ground contact, tape switches - which are band type switches - are inserted in the rubber sole of the foot in an array, as shown in figure 9.

To measure the force transferred from the machine to the ground, a single axis force sensor system was designed on a shank. A 1000N capacity commercial load cell (UMM-1000N, 1mV/V, Dacell, Korea) was used to measure for large amounts of force from the exoskeleton worn by the user. It can measure the force in the normal direction, so the force through the shank can be measured. The load cell basically responds to the normal force but also has crosstalk when a moment is applied.
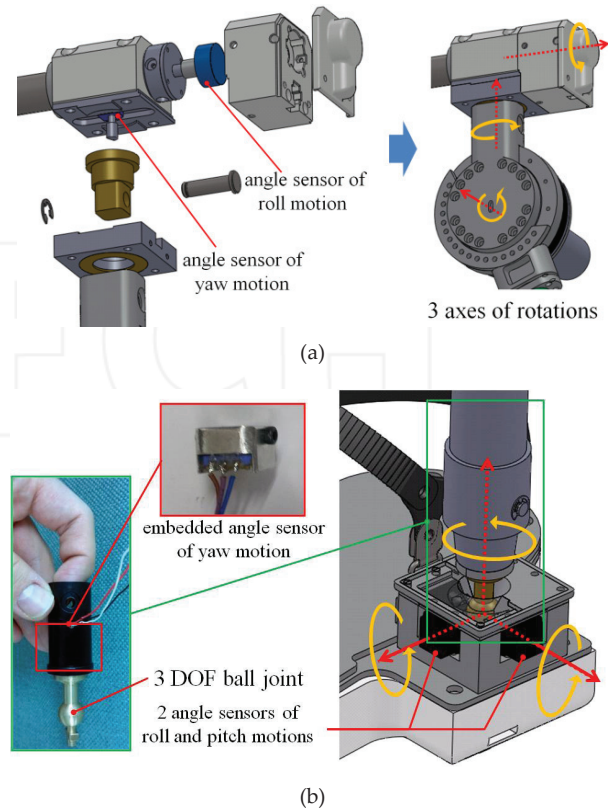

(a)

(b)

Figure 7. (a) Structure of the hip joints and angle sensors with potentiometers (b) Structure of the ankle joints and angle sensors with potentiometers
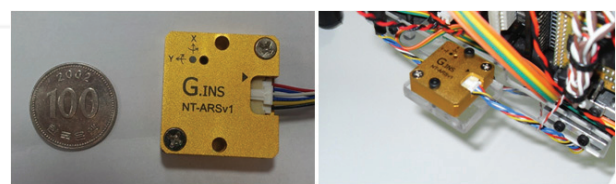

Figure 8. Inclinometer for the measurement of torso angles attached to the backbone of the exoskeleton
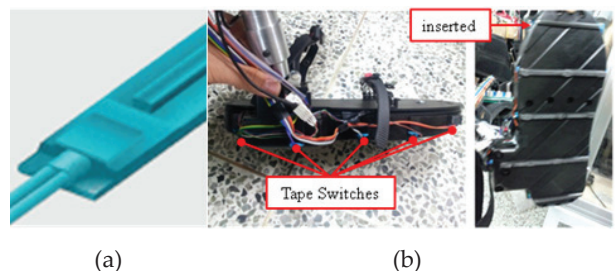

(a)   (b)

Figure 9. (a) Tape switch and (b) Ground contact sensor with horizontal tape switches in an array in the sole

To prevent an unwanted signal from the moment, proper housings for the load cell were designed - as

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shown in figure 10 - where the mechanism permits directional movement along the shank frame but protects the load cell from moment. There is lubricant on the walls of the housing contact to reduce friction between frames.

When the exoskeleton supports a person who cannot stand alone, human weight can be transferred to the ground through the shank frame of the exoskeleton as well as the robot foot on which the user stands. Therefore, we proposed to install 2 additional force sensors on the upper side of the robot foot to measure the force through the foot. The foot is composed of 2 rigid plates, 2 force sensors, a soft rubber sole and tape switches, as shown in figure 11. Low profile load cells connect two rigid upper and lower plates while maintaining a 2mm gap and can measure the force applied on the upper plate. As shown in figure 11 (a), the force sensor used in our system is a cantilever-type load cell extracted from a WII balance board (Nintendo, Japan), which is designed for the operation range of human weight. Since one end on the top surface of the cantilever is mounted on the upper plate with a bolt and the other end on the bottom surface is fixed to the lower plate, the human weight is transferred to the ground through the upper plate, two force sensors, a lower plate and a rubber sole, respectively. Due to the gap, the forces applied on the upper plate are transferred only though the force sensors.

The locations of force sensors were selected in consideration of the static pressure distribution of the human foot along the foot (walking) direction when a person is standing. Unlike a general humanoid robot, only two force sensors are installed in a foot module instead of using four sensors. In our exoskeleton robot, there is no actuator at the ankle roll joint and the motion in the sagittal plane can be controlled using pitch actuators. In this special condition, we expect that it is possible to obtain the CoP pattern with suitable accuracy, even though we determine the CoP position with a limited number of sensors. In addition, with the further use of crutches, the force signals at the tips of the crutches can be combined to determine the 2D position of the CoP. As the weight portion applied on the crutch is increased, the 2D position error of the CoP in a foot becomes negligible.

The auto ratchet elements are mounted on the upper plate so that the forces needed to connect the foot of the human and the exoskeleton do not affect the force sensor, regardless of whether the mount is tight or loose. The rubber sole is necessary to absorb the impact when the foot lands on the ground, and it is designed to enclose the tape switches and to be comfortable given irregular ground conditions.
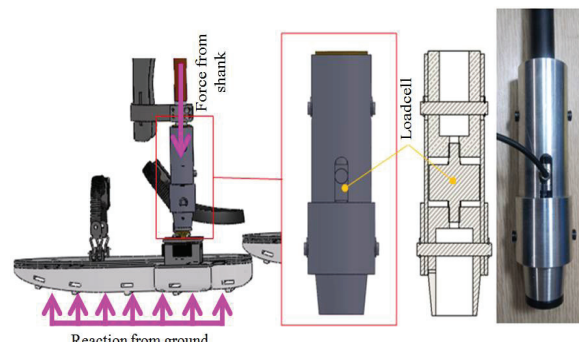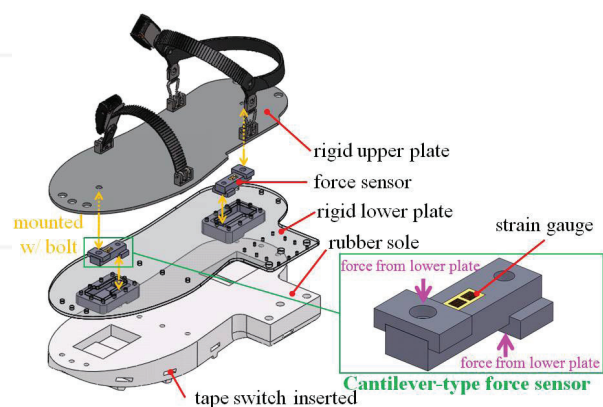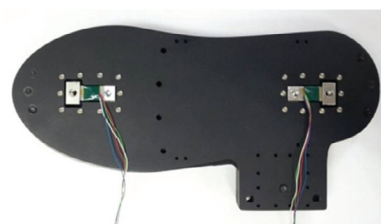

Figure 10. The force sensor system in a shank

(a)

(b)

Figure 11. (a) Foot module assembly drawing (b) Human-machine reaction sensors in the rubber sole

4.3 Actuators

The actuators on the pitch joints of the hip and knee are selected based on a simple approach considering two-dimensional planar motion in the sagittal plane. The torques and powers of human joints in the sagittal plane have been studied in numerous research for clinical gait analysis. Based on these, the required power of the actuator for the hip and knee is estimated at 200W. BLDC electric motors are selected as the actuators and harmonic drives have been selected, since they offer the advantage of compactness with a high gear ratio, which helps achieve a lighter design. For the hip joint, the actuator has 79.3Nm of torque in the maximum and the ability to be continuously operated at this torque level. The actuator set on the knee joint can bear 42.2Nm of continuous torque. Figure 12 (a) shows the actuator set, which consists of the motor and the harmonic drive. The proper BLDC

motor controller (Robocube, South Korea), as shown in figure 12 (b), has also been selected. The selected controller can control two BLDC motors with 200W power and is controlled by CAN (Controller Area Network) communication.

4.4 Data Acquisition System

There are 5 DSPs (TI, USA) modules - which are types of microcontroller units - on the exoskeleton to acquire sensor data and operate the device. One module is the main DSP and two modules are sensor DSPs for data acquisition, while another two modules are embedded in the motor controllers for the operation of the exoskeleton. The configuration of the data acquisition system in this paper is shown in figure 13 and CAN is used for communication between the devices. As shown in the figure, two sensor DSPs are used to acquire the sensor signals from each of the corresponding legs or crutches. These two DSPs send the acquired data to the main DSP, according to a "request" from the main DSP. This is useful for the synchronization of the two separate processors, because data transmission to the main DSP occurs only when requested. The inclinometer can also directly send the data to the main DSP according to the request using CAN communication. After acquiring data from two sensor DSPs and the inclinometer, the main DSP transmits the processed data to a PC.
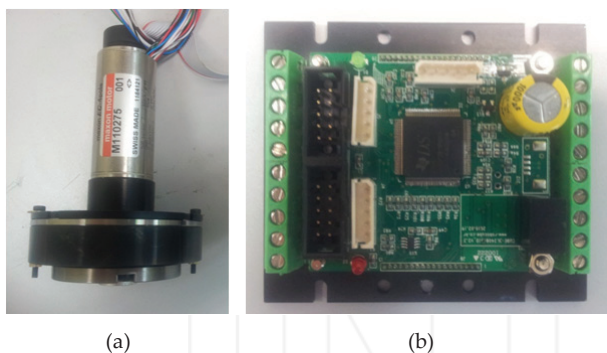

(a)   (b)

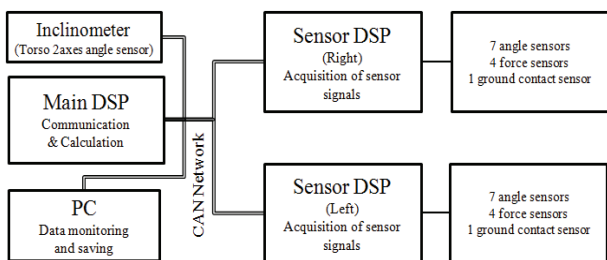**Figure 12.** (a) Actuator set of a BLDC motor and harmonic drive (b) Controller of the BLDC motor

Figure 13. Configuration of the data acquisition system configuration of the exoskeleton

(a)   (b)

Figure 14. The designed exoskeleton: (a) The exoskeleton (b) A wearer in the exoskeleton

5. Walking Experiment

A commercial pressure measurement system (TEKSCAN, USA) was used for a reference sensor to check the CoP in the experiment. The pressure sensor is a flexible thin mat with 136×52 cells of pressure sensors in an array and has dimensions of about 231.2cm×88.4cm. Figure 15 shows the experiments. The sampling speed of the pressure measurement system is set to 10Hz, owing to the heavy amount of arrayed pressure values and the sampling speed of the sensor data in the exoskeleton is set to 50Hz.

Figure 15. Walking experiments on a commercial pressure measurement system

In the experiment, a healthy person weighing 820N started walking on the pressure measurement system from a stationary posture and data was acquired in both

the pressure measurement system and the designed exoskeleton system.

The angles of the joints and torso are shown in figure 16 and the ground contact information measured by the tape switch arrays is displayed in figure 17. At the top of figure 17, the duration of the step on the ground based on the signals of tape switches for right and left feet is shown. The timing of step pivot change determined by the algorithm proposed in section 3.1 is shown at the bottom of figure 17. The positions of the exoskeleton are obtained by the measured angles and an example of a position analysis is shown in figure 18, representing several snapshots of walking.

The CoP can be found by using the calculated positions and normal forces of the contact points. The measured forces during walking are shown in figure 19. They are obviously cyclic. The CoP data calculated by the exoskeleton is compared with the measured values of the pressure measurement system, as shown in figure 20. The rms error between the two sets of CoP data in the time domain is about 31.4mm in the walking direction during one cycle of walking in those experiments with the calculated value, as shown in equation (9):

$$error = \sqrt{\frac{\left(\sum_{i}^{i+T} CoP_{calculated} - CoP_{pressure\ sensor}\right)^2}{T}} \quad (9)$$

where i is the initial moment and T is the period of a walking cycle. For the lateral walking direction, the rms CoP error is 36.4mm, and the rms distance error in 2D plane is measured by 48.1mm. The CoP error in the walking direction is smaller than that in the lateral direction, since the foot force sensors can only measure the CoP along the walking direction. Even though only a 1 dimensional CoP in the foot is used, there is little difference in the CoP in the forward and lateral directions.

In the precise walking control of a life-sized humanoid robot, this level of ZMP error will not be satisfactory and the safety margin during the single support phase becomes very small compared with the foot size. However, the CoP error in the experimental results is regarded as satisfactory in our application, since the exoskeleton robot for patients using forearm crutches has a larger support polygon and a slower walking speed compared with a general life-sized humanoid robot. When the support polygon is large, the safety margin of the CoP is increased. Moreover, the portion of the double support phase of the lower limb is increased at slow speed. The large area of the safety margin is confirmed by the observation that the existing exoskeleton robot can be stably operated - even without using the CoP information

- unlike a general humanoid robot. If a more accurate CoP is needed in the experiment with a real patient in the future, the modification of the location and the number of sensors in a foot can be considered.

Figure 21 shows the average forces measured from both sides of the shanks and feet during 1 cycle of walking. The total weight calculated by the force sensors of each leg resulted in almost equal levels: 472N on the right leg and 478N on the left. The average force supported by the shank was about 19.4% of the average total weight. The force sensor in the shank frame measures the partial weight of the human and the exoskeleton itself. Among the total 184N shank force, 130N is the weight of the exoskeleton. The average shank force supporting the human weight is thus 54N, which corresponds to 6.6% of the human weight. The ratio of weight supported by the shank over the human's weight can be used as an index of patient improvement in walking with regard to rehabilitation through later experiments. Although the experiments were processed with a healthy person due to difficulties in applying it to a real patient in the initial design process, the feasibility of the design in using CoP information in control and operation was shown.

6. Conclusion and Future Works

In this paper, a lower limb assistive exoskeleton device for paraplegic patients was designed. Mechanical hardware and a sensor system for an assistive exoskeleton device were designed by considering the CoP as a method of determining the human intention to walk and stability criteria. The lower limb exoskeleton has a 3 DOF hip, a 1 DOF knee and a 3 DOF ankle in a leg, making 14 DOF in total, so as to provide comfort to the wearer. Four joints of the hip and knee pitch in the sagittal plane are activated by an electric motor with gear sets. The force sensors in the foot modules and the load cell in the shank frame and ground contact sensors were designed to be used in the calculation of the CoP. The data is used in a theoretical analysis of the calculated positions and the CoP.

For the hardware validation of the designed lower limb exoskeleton, the calculated CoPs are compared with the data of a commercial pressure measurement system in the experiment. The experimental results show that the designed exoskeleton and embedded sensor system can estimate the CoP with reasonable accuracy.

Since a sensor system to measure the relative locations of the contact points of the crutch tip has not been constructed yet, its design will be introduced in a future study. The sensor functions must include the measuring locations of the contact points and the inclined angles of the crutches so as to determine the normal forces through the crutches. Using the same method in this study, the

CoP - including the crutch contact points - can be calculated if a walking experiment is performed with the added crutch sensor system. The operation of the exoskeleton using the CoP as a method of determining a walking intention and tests for the patients are left for future work.
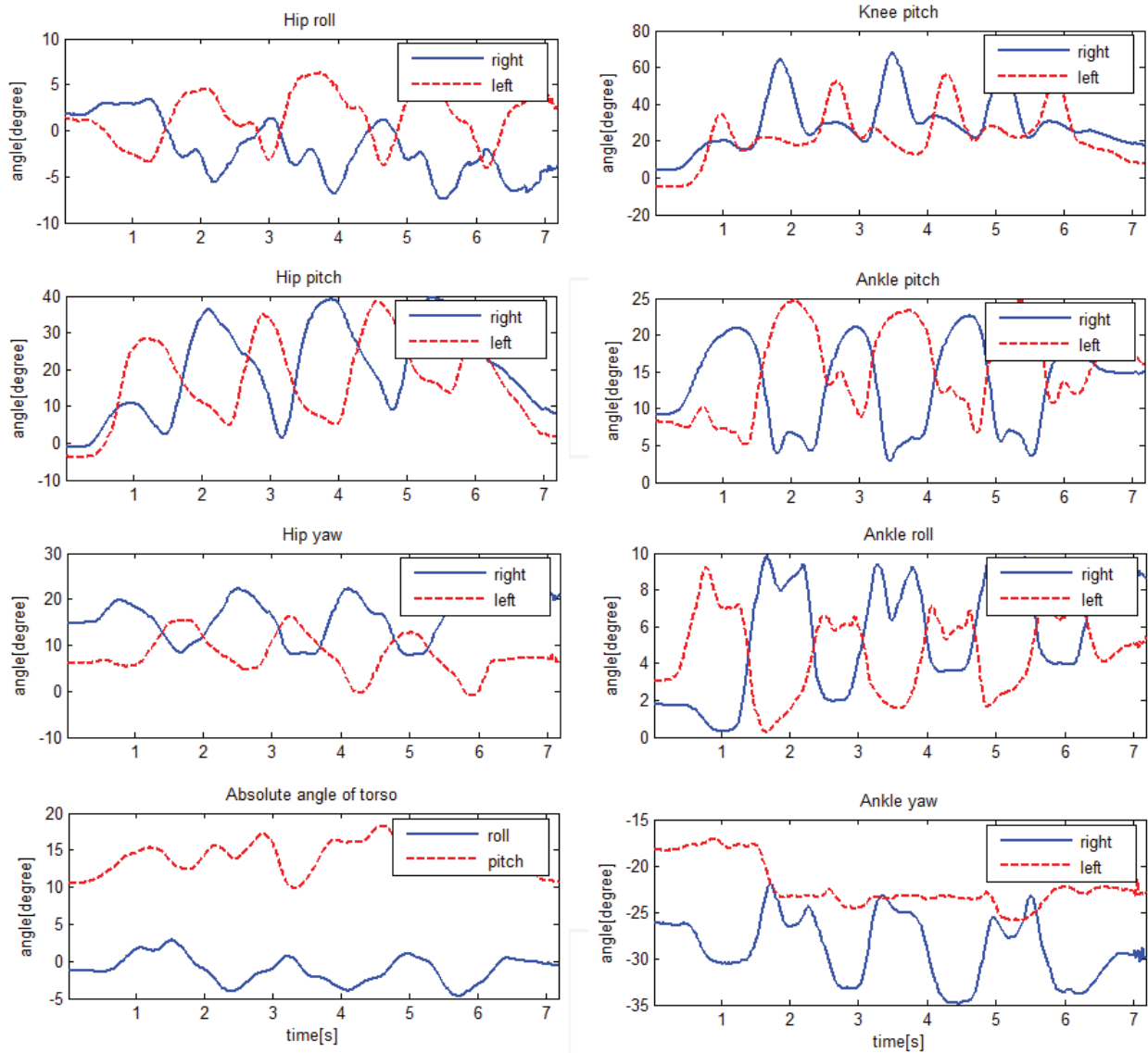

Figure 16. Joint angles and torso inclination while a person is walking in the exoskeleton
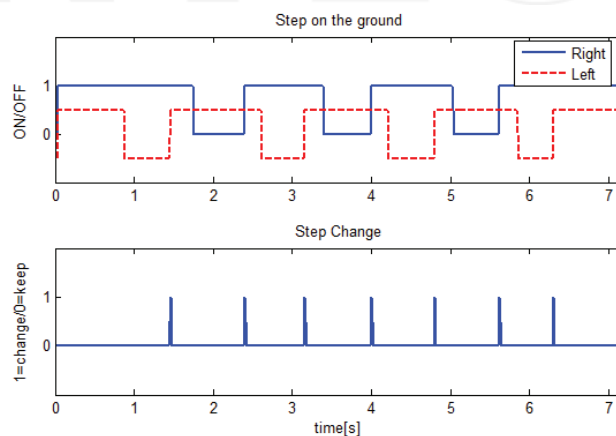

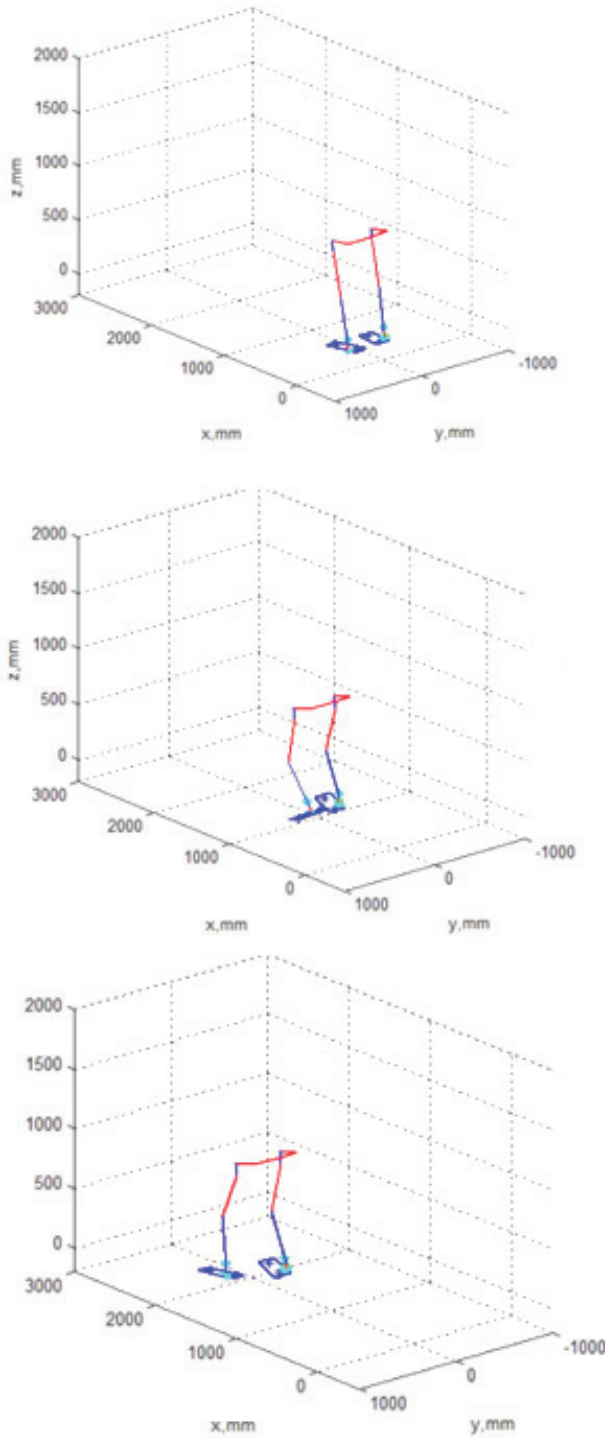**Figure 17.** Comparison of right/left foot step duration on the ground and (top) the timing of a step change (bottom)
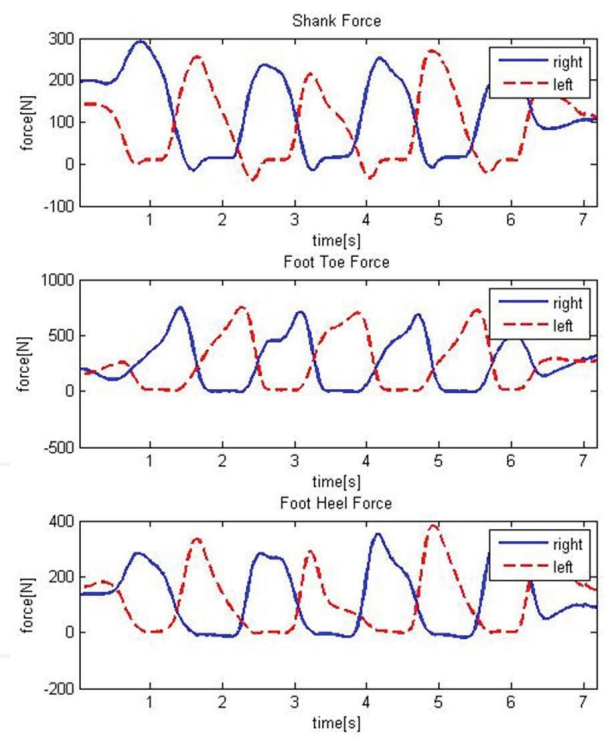
Figure 19. Forces on load cells while a person wearing the exoskeleton is walking: Shank (top), Foot Toe (middle) and Foot Heel (bottom)
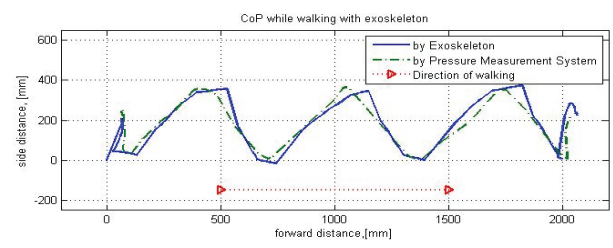

Figure 20. Comparison of the CoP trajectories of the exoskeleton while a person wearing the device is walking
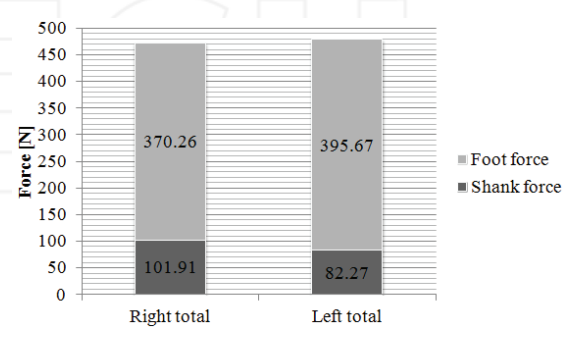

Figure 21. Average force applied on foot force sensors and the shank force sensor during 1 cycle of walking

6. Acknowledgments

Figure 18. Results of the position analysis of the exoskeleton while walking at t=0s, 3s, and 5s

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